On the Dynamical Stability of γ Cephei, an S-Type Binary Planetary System

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Abstract. Precision radial velocity measurements of the γ Cephei (HR8974) binary system suggest the existence of a planetary companion with a minimum mass of 1.7 Jupiter-mass on an elliptical orbit with a $\sim$2.14 AU semimajor axis and 0.12 eccentricity [1]. I present in this paper a summary of the results of an extensive numerical study of the orbital stability of this three-body system for different values of the semimajor axis and orbital eccentricity of the binary, and also the orbital inclination of the planet. Numerical integrations indicate that the system is stable for the planet's orbital inclination ranging from 0 to 60 degrees, and for the binary's orbital eccentricity less than 0.5. The results also indicate that for large values of the inclination, the system may be locked in a Kozai resonance.

INTRODUCTION

The existence of planets in binary star systems is no longer a mere idea. Approximately 35% of extrasolar planets discovered till 2002 exist in multiple star systems [2]. These systems are mostly wide binaries with separations between 500 and 750 AU, and with planets revolving around one of the stars. At such large distances, the perturbative effect of one star on the formation and dynamical evolution of planets around the other star is entirely negligible. A recently discovered Jupiter-like planet around the primary of the γ Cephei binary system is, however, an exception to this rule.

Gamma Cephei is a close spectroscopic binary composed of a 1.59 solar-mass K1 IV subgiant and a 0.4 solar-mass red M dwarf [3]. The semimajor axis of this system has been reported to have a lower value of 18.5 AU [1] and an upper value of 21 AU [4]. Precision radial velocity measurements suggest that a planet with a minimum mass of 1.7 Jupiter-mass revolves around the primary of this system on an elliptical orbit with an eccentricity of 0.12 ± 0.05 and a semimajor axis of approximately 2.14 AU. Being the first discovered S-type binary-planetary system[1], it is quite valuable to investigate whether this system is dynamically stable, and for what values of its orbital parameters its stability will remain. In this paper I present a summary of the results of an extensive numerical study of the dynamical stability of this system for different values of the orbital parameters of the binary and also the orbital inclination of the planet. A more comprehensive study of the dynamics of this system are to be published elsewhere.

[1] As classified by Rabl & Dvorak (1988), a binary-planetary system is called S-type when the planet revolves around one of the stars, and P-type when the planet revolves around the entire binary.

NUMERICAL ANALYSIS

An important quantity in determining the stability of a planet's orbit in a binary system is its semimajor axis. Rabl & Dvorak [5] and Holman & Wiegert [6] have presented an empirical formula for the maximum value of the semimajor axis of a stable planetary orbit in S-type binary-planetary systems. The value of the *critical semimajor axis*, a_c is given by

$$\begin{aligned} a_c/a_b = &(0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e_b \\ &+(0.586 \pm 0.061)\mu e_b + (0.150 \pm 0.041)e_b^2 + (-0.198 \pm 0.047)\mu e_b^2 \end{aligned} \tag{1}$$

where a_b is the semimajor axis of the binary, and $\mu = m_2/(m_1+m_2)$ and e_b represent the mass-ratio and orbital eccentricity of the binary, respectively. In the definition of the mass-ratio μ, m_1 and m_2 are the masses of the primary and secondary stars. To study to what extent equation (1) can be applied to the orbital stability of γ Cephei, this system was numerically integrated using a conventional Bulirsch-Stoer integrator. Numerical integrations were carried out for values of e_b ranging from 0.25 to 0.65 with steps of 0.05. When considered coplanar, the system was stable for all the values of $e_b < 0.5$ at all times. However, for the value of the binary eccentricity larger than 0.5, the system became unstable in less than 1000 years. Figure 1 shows the semimajor axes and eccentricities of the system for two cases of $e_b = 0.25$ and 0.45.

The stability of the system was also studied for different values of the orbital inclination of the planet. For each above-mentioned value of the binary eccentricity, the initial inclination of the orbit of the planet with respect to the plane of the binary was chosen from the values of 1, 5, 10, 20, 40, and 60 degrees. For values of $e_b < 0.5$, the system was stable for all inclinations less than 60 degrees. Figure 3 shows the results of sample runs for the values of the planet's orbital inclination equal to 5, 10, and 20 degrees. Also, as expected, in some cases of large inclinations and for eccentric binaries, the planet was locked in a Kozai resonance (Fig. 3).

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FIGURE 1. See Fig1.gif

FIGURE 2. See Fig2.gif

FIGURE 3. See Fig3.gif